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PROPERTIES OF MAR-AGING STEELS

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PROPERTIES OF MAR-AGING STEELS

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SUMMARY

Late in 1959, the International Nickel Company announced the development of a series of high-nickel martensitic steels which are strengthened by the precipitation-hardening mechanism. The steels are termed Mar-Aging steels because the precipitation reaction which accounts for their ultrahigh strength occurs on aging them when they are in the martensitic condition. These steels can be heat treated to yield strengths of 250,000 to 300,000 psi with reportedly excellent toughness in the presence of notches or cracks. The steels have the following nominal compositions:

Designation*	C	Ni	Co	Mo	Ti	Al	Cb
25 Ni	0.02	25	--	--	1.4	0.2	0.5
20 Ni	0.02	20	--	--	1.4	0.2	0.5
18 Ni Co Mo (250)	0.02	18	7	5	0.4	0.1	--
18 Ni Co Mo (300)	0.02	18	9	5	0.6	0.1	--

*The numbers in parenthesis refer to the nominal yield strength, in ksi, to which these steels can be heat treated.

The following room-temperature tensile properties have been developed in these steels by heat treatment:

Steel	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent in 2 inches	Notched* Tensile Strength, ksi
25 Ni	260	278	4.5	150
20 Ni	258	265	5.0	265
18 Ni Co Mo (250)	252	262	4.5	256
18 Ni Co Mo (300)	309	310	2.5	275

*Notch concentration factors (K_T) greater than 12.

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Cold working prior to maraging increases the yield and ultimate strength of these steels. Cold working up to about 50 per cent is reported to improve the notched tensile strength, while greater amounts of cold work are detrimental in this respect.

The high-nickel steels can be melted in air or in vacuum. They are readily forged and can be hot and cold rolled.

For the 20 Ni and 25 Ni steels, a dual heat treatment is required to obtain full strength. The first treatment is performed at 1300 F to condition the structure (which is austenite) for transformation to martensite on cooling to room temperature or to -100 F, and the second is an aging treatment at about 900 F to promote precipitation of the hardening phase, $Ni_3(Ti, Al)$, from the martensite. The 18 Ni Co Mo steels are martensitic as hot rolled or as annealed and require only an aging treatment at about 900 F to be fully hardened.

The Mar-Aging steels can be welded. Heat treatment after welding is necessary to obtain high strength in the weldments. Even with heat treatment, the ductility of weldments is reported to be considerably less than that of the base-plate material.

These steels are not corrosion-resistant materials. Even in mild atmospheres, they may be expected to show some signs of corrosive attack. Preliminary stress-corrosion cracking tests in industrial atmospheres and in aerated artificial sea water, however, have shown exceptional promise for the 18 Ni Co Mo steel.

It is the exceptional notch toughness at high strength levels that makes these steels particularly promising candidates for many high-strength applications. At high strengths, the notch toughness values reported for the Mar-Aging steels, particularly the 18 Ni Co Mo (250) steel, are significantly higher than those of other steels presently available. In addition, the simplicity of heat-treating weldments of the 20 Ni and the 18 Ni Co Mo (250) steels to obtain high strength and good toughness makes these steels particularly attractive for fabricating high-strength structural members. This is emphasized by the results of recent burst tests on the 18 Ni Co Mo (250) steel. In these tests, welded sub-size cylinders (6-inch diameter) failed with calculated burst stress values of 321,000 and 323,000 psi. These cylinders had simply been maraged at 900 F after welding.

These steels are presently being considered for rocket motor cases, pressure vessels, landing gear components, and ship plate.

Finally, the Mar-Aging steels are not laboratory curiosities. Heats up to 20 tons have been produced. Good reproducibility of mechanical properties has been obtained between laboratory and production heats, as well as among heats produced by different steel mills.

Undoubtedly there will be trials and pitfalls in the application and use of these steels, as there are in the use of any high-strength material. There is nothing to indicate, however, that problems in fabrication and use cannot be eliminated or circumvented. If the properties and characteristics reported for these steels are reproducible and consistent, then a very significant step forward will have been made in the development of superior high-strength materials.

INTRODUCTION

The development of a series of high-nickel martensitic steels strengthened by the precipitation hardening mechanism was announced by the International Nickel Company late in 1959. The steels, termed Mar-Aging steels, are reportedly heat treatable to yield strengths of 250,000 to 300,000 psi with excellent toughness in the presence of notches or cracks.

Since the initial release of data on these steels, considerable effort has been expended in optimizing their composition, in studying their properties, and in evaluating them for various defense applications. Several companies have been licensed to produce the steels. Although still in the development stage, the steels show significant promise for aerospace applications.

This memorandum presents properties on four Mar-Aging steels. The data were taken from publications and reports of the International Nickel Company, Curtiss-Wright Corporation, and Allegheny Ludlum Steel Corporation. Allegheny Ludlum is a producer of the Mar-Aging steels, and Curtiss-Wright has been carrying out a research program under the sponsorship of the Air Force, to evaluate and develop these steels further for missile cases and aircraft structural components.

TERMINOLOGY OF MAR-AGING STEELS

Numerous steels containing 18 to 25 per cent nickel have been studied. Up to the present, four specific compositions have emerged. As yet, these bear no standard designations. For simplicity in this memorandum, the following designations are employed for the four compositions:

Designation*	C	Ni	Co	Mo	Ti	Al	Cb
25 Ni	0.02	25	--	--	1.4	0.2	0.5
20 Ni	0.02	20	--	--	1.4	0.2	0.5
18 Ni Co Mo (250)	0.02	18	7	5	0.4	0.1	--
18 Ni Co Mo (300)	0.02	18	9	5	0.6	0.1	--

*The numbers in parentheses refer to the nominal yield strength, in ksi, to which these steels can be heat treated.

METALLURGICAL CONSIDERATIONS

In many respects, the metallurgy of the Mar-Aging steels resembles that of the precipitation-hardenable stainless steels. The Mar-Aging steels

have sufficient alloy content to lower the M_s temperature to near or below room temperature. Austenite decomposition does not occur above the M_s temperature; that is, neither pearlite nor bainite is formed in these steels. As a consequence, the rate of cooling from high temperature is not a critical factor in hardening. The steels are hardened by transforming the austenitic structure into martensite and subsequently aging the martensite to promote precipitation hardening. The steels get their name from this last step in the hardening procedure. The martensitic structure does not revert to austenite on heating until a temperature of about 1000 F is exceeded.

The 25 Ni steel was designed to be austenitic and, thus, soft and readily fabricated as annealed. To harden this steel, the austenitic structure must first be conditioned (ausaged) for transformation to martensite. This is done by treating at 1100 to 1300 F to precipitate titanium compounds, presumably Fe_2Ti, thus raising the M_s temperature so that the austenite will transform to martensite on cooling to room temperature. On maraging at 800 to 900 F, precipitation of nickel-titanium-aluminum compounds [presumably $Ni_3(Ti, Al)$] from the martensitic matrix occurs, resulting in significant increases in strength. To develop maximum strength, the steel must be essentially entirely martensitic before maraging. This necessitates refrigeration at -100 F prior to maraging in order to transform retained austenite in the structure.

Cold working is known to raise the M_s temperature of austenitic iron alloys. Consequently, cold working may serve as a substitute for the ausaging treatment. Nevertheless, refrigeration at -100 F subsequent to cold working is required to insure complete transformation to martensite.

The 20 Ni steel, because of its lower nickel content, has an M_s temperature above room temperature and, therefore, is essentially martensitic as annealed or as hot rolled. To insure complete transformation to martensite, refrigeration is recommended. Aging in the range of 800 to 950 F causes precipitation of $Ni_3(Ti, Al)$ and concomitant development of high strength.

The 18 Ni Co Mo steel has a still higher M_s temperature and consequently becomes completely martensitic on cooling to room temperature after hot rolling or annealing. Refrigeration is not required to develop a fully martensitic structure. Aging in the range of 800 to 950 F causes the precipitation of presumably a cobalt-molybdenum-titanium phase, resulting in high strength.

The martensite in the Mar-Aging steels is of very low carbon content (less than 0.03 per cent). As such, it is relatively soft and formable; low-carbon martensite work hardens quite slowly and consequently is capable of withstanding extensive cold reduction. Low carbon content appears to be responsible for the excellent toughness of these alloys.

PRODUCTION CHARACTERISTICS

Melting

The Mar-Aging steels may be melted in air by arc or induction methods as well as melted by vacuum induction and consumable-electrode

methods. Regarding the 25 Ni steel, vacuum-melted material has developed somewhat higher strength than has air-melted material. Ductility has not been improved by vacuum melting. With respect to the 20 Ni steel and the 18 Ni Co Mo steels, vacuum-melted stock has developed better ductility and notch toughness than have been obtained by air melting.

Forging

The Mar-Aging steels should be soaked and forged at 2200 to 2300 F. Forging should be finished at about 1500 F for grain-size control and optimum mechanical properties after heat treatment. The forging behavior of the Mar-Aging steels is about the same as that of a medium alloy steel. In some instances, titanium segregation has not been eliminated in a single upset forging operation; substantial reductions in forging and intermediate soaking have been required.

Rolling

The Mar-Aging steels are readily hot rolled in the temperature range of 1900 to 1500 F. Again, finishing at about 1500 F is necessary for grain-size control.

The Mar-Aging steels are readily cold rolled. All four types have been cold reduced as much as 90 per cent between anneals. Even those steels that are martensitic at room temperature are readily cold rolled. This is attributed to the fact that low-carbon martensite work hardens slowly.

Fabrication

Welding. Welding is considered in detail in a later section of this memorandum.

Machining. Based on limited tests, the 20 Ni and 25 Ni steels have a machinability rating about 50 per cent that of free-machining stainless steels. In the annealed condition, the steels are gummy and susceptible to tearing. Better finishes, higher machining rates, and improved tool life are obtained on fully hardened material. The 18 Ni Co Mo steels in the annealed condition appear to machine somewhat more readily than the 20 Ni and 25 Ni steels as annealed or as hardened.

Forming. Little information on the forming characteristics of these steels is available at present. Even though the steels work harden very slowly, the ductility in the annealed condition, as measured by elongation in 2 inches, is only 15 to 25 per cent. Consequently, extensive stretching and deep drawing will require intermediate annealing.

PROPERTIES OF MAR-AGING STEELS

The following sections present information on the properties of the four Mar-Aging steels. Tables summarizing pertinent mechanical properties are contained within the body of the report. Tables going into greater detail are presented in the Appendix.

25 Ni Steel

Composition

At the present time, the following composition range appears to give the optimum combination of yield strength and notch toughness:

Element	Per Cent
Carbon	0.03 maximum
Nickel	25.0 - 26.0
Titanium	1.30 - 1.60
Aluminum	0.15 - 0.30
Columbium	0.30 - 0.50
Boron	0.003 added
Zirconium	0.02 added
Calcium	0.05 added
Manganese	0.10 maximum
Silicon	0.10 maximum
Phosphorus	0.01 maximum
Sulfur	0.01 maximum

Physical Properties

The following physical properties have been determined for the 25 Ni steel:

Density	7.92 g/c.c. or 0.286 lb/in.^{3}
Linear coefficient of expansion, RT to 800 F	6.3×10^{-6} in/in/F (determined on specimens having a 90% martensitic structure)
Modulus of elasticity at room temperature	24 to 25 million psi
Melting range	2650 - 2750 F
Poisson's ratio	0.31

Mechanical Properties at Room Temperature

While no typical or guaranteed properties have yet been established for this steel, sufficient data have been accumulated to indicate generally the properties that can be developed. Of course, the mechanical properties attained are dependent upon the heat treatment employed. Table 1 shows the room-temperature tensile properties of bar stock and sheet for the 25 Ni steel after various heat treatments.

Cold rolling tends to eliminate the ausaging (or austenite conditioning) treatment and at the same time improves the strength obtained on subsequent maraging. As shown in Table 2, cold rolling up to 50 per cent reduction in thickness is beneficial to notched tensile strength. Cold reductions of 75 per cent, however, are quite detrimental to notched tensile strength.

Elevated-Temperature Properties

Elevated-temperature tensile data were available only for an alloy cold rolled 50 per cent and aged at 900 F for 1 hour. In this condition, the steel had a room-temperature tensile strength of about 290,000 psi. As the testing temperature was increased, there was a gradual reduction in strength up to about 700 F, above which the strength dropped rapidly. Creep and rupture properties were not available.

Cryogenic Properties

Only a few cryogenic-temperature tests have been made thus far on the 25 Ni steel. The data available are presented in Table 3 and suggest that this steel will show a good combination of strength and ductility at low temperatures.

Fatigue Strength

Data obtained by Curtiss-Wright have shown a fatigue limit at 10^7 cycles of about 95,000 psi for the 25 Ni steel cold rolled 50 per cent and aged one hour at 900 F.

Heat Treatment

The heat treatment involved in hardening the 25 Ni steel comprises: (1) solution annealing at 1500 ± 25 F for one hour followed by air cooling, (2) ausaging (austenite conditioning) at 1100 to 1300 F for four hours followed by air cooling, (3) refrigerating at -100 F for 16 hours followed by air warming, (4) maraging at 800 to 900 F for 1 to 4 hours followed by air cooling.

TABLE 1. ROOM-TEMPERATURE TENSILE PROPERTIES OF 25 Ni STEEL

Condition[a]	Direction[b]	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction of Area, per cent	Notched Tensile Strength[c], ksi
			Bar Stock			
A 1500	-	38	105	34	77	-
A 1500 + a 1300 + R + M 800	-	250	265	12	53	306
A 1500 + a 1300 + R + M 850	-	255	270	11.5	53	285
A 1500 + a 1300 + R + M 900	-	268	279	12	51	238
			Sheet			
A 1500	T	42	104	30	-	-
	L	41	104	26	-	-
A 1500 + a 1300	T	226	248	8	-	-
+ R + M 800	L	225	245	9	-	209
A 1500 + a 1300	T	262	284	4.5	-	-
+ R + M 850	L	258	272	4.5	-	150
A 1500 + a 1300	T	248	263	4.0	-	-
+ R + M 900	L	241	260	4.5	-	118
A 1500 + a 1300	T	242	261	4.0	-	-
+ R + M 950	L	240	249	6.5	-	-

(a) A 1500 - annealed at 1500 F for 90 minutes per inch of section.
a 1300 - ausaged at 1300 F for 4 hours.
R - refrigerated at -100 F for 16 hours.
M - maraged at the designated temperature for 1 to 4 hours.

(b) T - transverse.
L - longitudinal.

(c) For bar stock, K_t was greater than 10.
For sheet stock, K_t was greater than 10.

TABLE 2. ROOM-TEMPERATURE TENSILE PROPERTIES OF COLD-ROLLED AND MAR-AGED SHEET SPECIMENS OF 25 Ni STEELS

Condition(a)	Direction	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Notched Tensile Strength(b), ksi
A 1500	T	42	104	30	-
	L	41	104	26	-
A 1500 + C 25	T	261	278	4	205
+ R + M 800	L	254	268	4	211
A 1500 + C 25	T	259	282	4	199
+ R + M 850	L	249	263	5	-
A 1500 + C 50	T	79	137	14	-
A 1500 + C 50	T	273	272	2	224
+ R + M 850	L	262	273	4	228
A 1500 + C 50	T	251	274	3	232
+ R + M 950	L	230	259	4	233
A 1500 + C 75	T	94	141	13	-
A 1500 + C 75 + M 800	T	288	300	3	134
A 1500 + C 75 + M 850	T	304	318	3	115
A 1500 + C 75	T	283	288	2	-
+ R + M 850	L	287	290	2	-

(a) A 1500 - annealed at 1500 F.
C - cold rolled indicated amount.
R - refrigerated at - 100 F for 16 hours.
M - maraged at indicated temperature.

(b) Center-notched specimen having K_T greater than 12.

TABLE 3. TENSILE PROPERTIES OF 25 Ni SHEET SPECIMENS[a] AT SUBZERO TEMPERATURES

Direction	Temperature	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent
T	Room	98	152	6.0
L	Room	110	144	7.5
T	-100 F	116	172	2.8
L	-100 F	103	171	6.8
T	-320 F	161	224	8.0
L	-320 F	167	220	11.2

(a) All specimens were annealed at 1500 F and cold rolled 50 per cent; the specimens were not aged.

The solution anneal produces recrystallization and complete austenization. The 1500 F annealing treatment for one hour has been found to produce the highest strength and best ductility in material subsequently hardened. Higher annealing temperatures result in reduction in strength and ductility (see Table A-1).

The ausaging temperature is reportedly not critical, but the time should be sufficient to permit precipitation of the Ni_3(Ti, Al) and Fe_2Ti compounds to raise the M_s temperature the needed amount to obtain complete transformation on refrigeration.

The refrigeration time of 16 hours has thus far been arbitrarily selected to insure complete transformation of austenite to martensite. Data on the completeness of transformation after various refrigeration times were not available.

Maximum strength is obtained by maraging at 900 F for one hour or at 850 F for four hours. Complete data on the effect of maraging time and temperature on strength properties were not available.

The hardening schedule, wherein cold working is substituted for ausaging, is as follows:

(1) Solution anneal at 1500 F for 1 hour and air cool.

(2) Cold work. The optimum degree has not yet been established. Cold reductions of 25, 50, and 75 per cent have been investigated. Sufficient cold work should be employed to raise the M_s temperature enough to insure complete transformation on subsequent refrigeration.

(3) Refrigerate at -100 F for 16 hours, air warm.

(4) Marage at 800 to 900 F for 1 to 4 hours, air cool.

This treatment results in greater strength and toughness than is obtainable through heat treatment alone.

Control of Composition

Because the 25 Ni steel derives much of its strength from the precipitation of titanium compounds, Ni_3(Ti, Al) and Fe_2Ti, careful control of titanium content is required. Lowering the titanium content below 1.3 per cent will result in reduced strength. Increasing the titanium content above 1.6 per cent will lower the M_s temperature of the steel. Unless the ausaging time is increased, precipitation of titanium compounds will be insufficient to raise the M_s temperature to the desired range, and reduced strength will result. In addition, titanium contents above 1.6 per cent will result in reduced notch toughness.

Aluminum additions enhance the strengthening effects of titanium compounds. However, aluminum contents above 0.35 per cent cause a drastic reduction in notched tensile strength.

Carbon is maintained in the range of 0 to 0.03 per cent. Carbon contents above 0.03 per cent tie up titanium as titanium carbide, reducing the effective titanium content. This results in reduced strength. Increased carbon content also reduces notch toughness.

Manganese and silicon are restricted to 0.10 per cent maximum to maintain good notch toughness. Higher manganese contents also tend to cause retained austenite and reduced strength.

Columbium, boron, and zirconium are added to improve notch toughness. For the effect of boron and zirconium see Table A-2.

Finally, nickel is held within the range of 24.5 to 26.5 per cent. Alloys containing less than 24.5 per cent nickel will have a tendency to be martensitic on cooling from the annealing temperature and will not be so readily fabricable. Higher nickel contents will result in retained austenite and reduced strength.

Again, close control of composition and heat treatment is required to obtain the properties reported. Careful control is mandatory to have readily fabricable material as annealed and to obtain high strength as heat treated.

Welding

The International Nickel Company has reported that the 25 Ni steel can be welded readily by the inert-gas-shielded tungsten arc process (TIG). Curtiss-Wright has also reported little difficulty in welding this steel using the TIG process.

Weldments made with filler wire of the same composition as the base metal showed no cracking or porosity and could be bent 180 degrees around a 1-T radius. The full strength properties of the base plate were not obtained in the weldments on refrigeration at -100 F and maraging at 850 F, as shown below:

Material	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, psi
Base Plate	268	283
Weldment	198	199

The reduced strength in the weldment resulted from loss of titanium and aluminum during welding and incomplete martensitization of the weld deposit and the weld-heat-affected zone. Cold working the weld 50 per cent prior to heat treatment resulted in strength properties essentially equal to those in the base plate.

Increasing the titanium and aluminum contents of the filler wire did not result in full strength in refrigerated and maraged joints. Optimum strength in weldments, approaching that of the base plate, has been obtained by ausaging the material at 1300 F prior to refrigeration and maraging. Drastic reductions in ductility, however, have resulted from this procedure. Efforts to improve the weldability of the 25 Ni steel are continuing.

Corrosion Resistance

The International Nickel Company has reported that the general corrosion rate of the 25 Ni steel in salt atmosphere is about 0.3 mil per year. This rate is about one-tenth that of the 4130 and 4340 types of engineering steel.

The number of stress-corrosion tests made thus far is too limited to ascertain the resistance of the 25 Ni steel to stress corrosion cracking.

20 Ni Steel

Composition

At the present time, the following composition range appears to give the optimum combination of properties:

Element	Per Cent
Nickel	19.0 - 20.0
Titanium	1.3 - 1.6
Aluminum	0.15 - 0.30
Columbium	0.30 - 0.50
Boron	0.003 added
Zirconium	0.02 added
Calcium	0.05 added
Carbon	0.03 maximum
Manganese	0.10 maximum
Silicon	0.10 maximum
Phosphorus	0.01 maximum
Sulfur	0.01 maximum

Physical Properties

The following physical properties have been determined for the 20 Ni steel:

Density	7.92 g/c.c. or 0.286 lb/in.^{3}
Linear coefficient of expansion, RT to 800 F	6.3 x 10^{-6} in./in./F (determined on specimens having a 90 per cent martensitic structure)
Modulus of elasticity at room temperature	24 to 25 million psi
Melting range	2650 to 2750 F
Poisson's ratio	0.31

Mechanical Properties

Typical or guaranteed properties have not yet been established for the 20 Ni steel. Representative properties are listed in Table 4. The high notched tensile strengths reported both for sheet and for bar specimens are noteworthy.

Cold work tends to eliminate the necessity for the refrigeration treatment and to enhance the strength of the 20 Ni steels, as shown in Table 5. As can be seen in this table, however, 50 per cent or more cold work reduces the notch toughness of the steel, particularly in the transverse direction.

Elevated-temperature tensile data and rupture properties are not available for this steel. Likewise, fatigue data are not available.

Cryogenic-temperature tensile properties for the 20 Ni steel are given in Table 6.

Heat Treatment

The heat treatment employed to harden the 20 Ni steel is considerably simpler than that employed for the 25 Ni steel. The treatment involves:

(1) Annealing at 1500 F ± 25 to austenitize and recrystallize the structure.

(2) Air cooling to room temperature, during which austenite transforms to martensite.

(3) Refrigerating at -100 F for 16 hours, or cold rolling, to insure complete transformation of the austenite to martensite.

(4) Maraging at 800 to 950 F for 1 to 4 hours to cause precipitation of $Ni_3(Ti, Al)$ compounds, thereby fully hardening the steel.

TABLE 4. ROOM-TEMPERATURE TENSILE PROPERTIES OF 20 Ni STEEL

Condition[a]	Direction	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation in 2 inches, per cent	Reduction of Area, per cent	Notched Tensile Strength[b], ksi
			Bar Stock			
A 1500	-	110	150	26	69	-
A 1500 + R + M 850	-	250	260	12	60	360
A 1500 + R + M 900	-	260	270	12	60	-
			Sheet Stock			
A 1500	T	115	155	9	-	-
	L	115	153	8	-	-
A 1500 + R +	T	260	269	4.5	-	260
M 850	L	256	264	6	-	271
A 1500 + R +	T	246	257	3.5	-	248
M 900	L	244	256	4.5	-	256
A 1500 + R +	T	243	252	4	-	280
M 950	L	240	250	4.5	-	272

(a) A - annealed at 1500 F.
R - refrigerated at -100 F for 16 hrs.
M - maraged at indicated temperature for 1 to 4 hours.

(b) For bar stock a notch radius of less than 0.001 inch (K_T greater than 10) was employed.
For sheet specimens, both edge and center notches having notch radii less than 0.001 inch (K_T greater than 12) were employed.

TABLE 5. ROOM-TEMPERATURE TENSILE PROPERTIES OF COLD-WORKED AND MAR-AGED SHEET SPECIMENS OF 20 Ni STEEL

Condition	Direction	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Notched Tensile Strength, ksi
A 1500 + R + M 850	T	260	269	4.5	260
	L	256	263	6.0	271
A 1500 + C 25 +	T	254	256	4.0	-
R + M 850	L	267	272	4.8	-
A 1500 + C 50 +	T	264	281	3.3	191
M 850	L	264	273	4.2	211
A 1500 + C 50 +	T	263	271	3.5	116
R + M 850	L	259	263	4.0	193
A 1500 + C 75 +	T	305	308	1.3	-
M 850	L	296	303	1.8	-
A 1500 + R + M 900	T	246	257	3.7	248
	L	244	256	4.7	256
A 1500 + C 50 +	T	279	293	3.7	180
M 900	L	273	281	4.0	213
A 1500 + C 50 +	T	278	285	3.3	118
R + M 900	L	268	272	4.0	214

TABLE 6. TENSILE PROPERTIES OF 20 Ni STEEL
SPECIMENS AT SUBZERO TEMPERATURES

Condition	Direction	Temperature	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Notched Tensile Strength, ksi
A 1500 + C 50	T	Room	149	176	2.0	188
	L	Room	153	165	2.0	199
A 1500 + C 50	T	-100 F	169	199	0.5	221
	L	-100 F	158	186	3.0	203
A 1500 + C 50	T	-320 F	221	241	2.8	268
	L	-320 F	217	228	5.5	253
A 1500 + C 50	T	-423 F	-	-	-	346
	L	-423 F	-	219	-	355

These heat treatments can be performed in air.

The effects of variations in annealing time and temperature have not as yet been established. Higher strength and better ductility are produced in fully heat treated material by solution annealing at 1500 F for 15 minutes rather than at 1600 F for 1 hour.

Maximum strength and ductility are obtained by maraging at 850 to 900 F. Higher or lower aging temperatures result in somewhat lower strength.

Cold work after refrigeration but prior to maraging produces only moderate increases in strength up to about 50 per cent cold reduction. Cold reductions above 50 per cent increase strength rapidly and decrease ductility.

The effects of varying maraging time and temperature after cold reductions from 0 to 90 per cent are given in Table A-11. For all levels of cold reduction, maximum strength was produced by maraging at 900 F. For cold reductions of 30 per cent or more, maximum strength was produced in one hour (the minimum maraging time studied). Maximum fracture toughness, however, was not obtained on maraging at 900 F (see Table A-13). Higher fracture toughness was obtained by maraging at either 850 or 950 F in material not cold rolled prior to maraging. For material cold rolled and maraged, much higher fracture toughness was obtained by maraging at 950 F than at the other two temperatures.

Control of Composition

As is the case with the 25 Ni steel, the 20 Ni steel derives the bulk of its strength from the precipitation of titanium compounds. As a consequence, close control of titanium content is mandatory. As shown in Table A-10, increasing the titanium content from 1.32 to 1.90 per cent increases yield and tensile strength but tends to reduce fracture toughness. To maintain a notched-tensile-strength to yield-strength ratio of 1.0, the titanium content is restricted to 1.6 per cent maximum.

To obtain complete transformation on refrigeration, the nickel content must be controlled below a maximum value. At present, the maximum nickel content acceptable is believed to be 20.0 per cent.

Thus far, no benefits have been observed from zirconium and boron additions. The effect of aluminum variations has not been reported as yet. As is the case with the 25 Ni steel, limitation of the manganese and carbon contents is essential to obtain both complete transformation on refrigeration and good fracture toughness.

Welding

The International Nickel Company reports that sound welds can be produced by coated electrode, inert-gas-consumable electrode, or inert-gas tungsten-arc methods. Electrodes of the same composition as the base plate are recommended. No preheat is required. Welded material must be maraged at 850 to 900 F to obtain high strength in the weld deposit and heat-affected zone.

The following properties were obtained on a weldment of the 20 Ni steel by the International Nickel Company:

Heat Treatment	0.2 Per Cent Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction of Area, per cent
850 F - 1 hour	251	256	1.2	10.3
850 F - 2 hours	254	258	1.0	5.1

It will be noted that, while the strength of the weldment was essentially equal to that normally obtained in parent metal, the ductility was much less.

Corrosion Resistance

No corrosion data are available at the present time. However, International Nickel Company and Curtiss-Wright are currently conducting general and stress-corrosion tests on the 20 Ni steel.

18 Ni Co Mo Steel (250)

Composition

Presently, the suggested composition for the 18 Ni Co Mo (250) steel is as follows:

Element	Per Cent
Nickel	17.0 - 19.0
Molybdenum	4.6 - 5.1
Cobalt	7.0 - 8.0
Titanium	0.30 0.50
Aluminum	0.10 added
Boron	0.003 added
Zirconium	0.02 added
Calcium	0.05 added
Carbon	0.01 - 0.03
Manganese	0.10 maximum
Phosphorus	0.01 maximum
Sulfur	0.01 maximum
Silicon	0.10 maximum

Physical Properties

The following physical properties have been reported for the 18 Ni Co Mo (250) steel:

Density	7.93 g/c.c. or 0.289 lb/in.^{3} (determined on specimens in the A 1500 + M 900 condition)
Linear coefficient of thermal expansion, RT to 900 F	5.6 x 10^{-6} in./in./F
Modulus of elasticity at room temperature	26.5 to 27.5 million psi
Modulus of rigidity at room temperature	10.2 million psi
Electrical resistivity at room temperature	60.5 microhm-cm for A 1500 condition 38.5 microhm-cm for A 1500 + M 900 condition
Poisson's ratio	0.30

Mechanical Properties

Room-temperature tensile properties reported for the 18 Ni Co Mo (250) steel are summarized in Table 7. Again, the high notched-tensile strengths of this steel are noteworthy.

Cryogenic-temperature tensile properties are given in Table 8. Charpy impact properties are given in Table 9.

Elevated-temperature properties of these steels are given in Table 10. The data listed are for material annealed at 1500 F and maraged at 900 F. The International Nickel Company has reported, however, that optimum elevated-temperature properties are obtained by annealing at 1800 F instead of at 1500 F, prior to aging.

Fatigue data are not available.

The International Nickel Company has reported a shear strength of 143,000 psi and a compressive yield strength of 247,000 psi for plate stock having a tensile yield strength of 230,000 psi.

Burst Tests

The results of burst tests performed by Curtiss-Wright on the 18 Ni Co Mo (250) steel are as follows:

TABLE 7. ROOM-TEMPERATURE TENSILE PROPERTIES OF 18 Ni Co Mo (250) STEEL

Condition	Direction	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction of Area, per cent	Notched Tensile Strength, ksi
			Plate			
Hot Rolled + M 900	-	245	250	12	57	387
A 1500	T	109	150	14	60	-
	L	107	148	17	70	-
A 1500 + M 900	T	245	252	9.5	46	355
	L	241	246	12.5	55	363
			Bar			
A 1500	-	116	146	19	72	-
A 1500 + M 900	-	262	271	12	58	399
A 1500 + C 50 + M 900	-	267	273	12	58	415
			Sheet			
A 1500	T	118	150	8	-	-
A 1500 + M 900	L	252	262	4.5	-	263
A 1500 + C 50 + M 900	L	290	292	2.5	-	261

TABLE 8. CRYOGENIC-TEMPERATURE TENSILE PROPERTIES OF 18 Ni Co Mo (250) STEEL

Condition	Direction	Temp.	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction of Area, per cent	Notched Tensile Strength, ksi
			Plate				
A 1500 + M 900	T	RT	232	243	10	44	-
A 1500 + M 900	T	-320 F	292	310	7	29	-
A 1500 + M 900	L	RT	232	243	12	57	-
A 1500 + M 900	L	-320 F	291	305	9	40	-
			Sheet				
A 1500 + M 900	L	RT	250	262	4.5	-	256
	L	-320 F	315	329	4.5	-	244
A 1500 + C 50 + M 900	L	RT	286	289	3.5	-	265
	L	-320 F	335	338	0	-	266

TABLE 9. CHARPY IMPACT PROPERTIES OF 18 Ni Co Mo (250) STEEL PLATE

Condition	Direction	Temperature	Charpy V-Notch Energy, ft-lb
A 1500	T	Room	42
A 1500	L	Room	97
A 1500 + M 900	T	Room	18
A 1500 + M 900	L	Room	24
A 1500 + M 900	-	0F	24
A 1500 - M 900	-	-100 F	21
A 1500 - M 900	-	-175 F	21
A 1500 + M 900	-	-244 F	20
A 1500 + M 900	-	-320 F	20

TABLE 10. ELEVATED TEMPERATURE PROPERTIES OF 18 Ni Co Mo (250) STEEL

Tensile Properties

Condition	Temperature, F	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation in 1 inch, per cent	Reduction of Area, per cent
A 1500 + M 900	800	209	221	12	56
	900	184	198	19	66
	1000	138	154	24	74

Stress-Rupture Properties

Condition	Temperature, F	Stress, psi	Life, hr	Elongation, per cent	Reduction of Area, per cent
A 1500 + M 900	800	175,000	38	13	51
		150,000	561	13	59
	900	150,000	6.7	17	63
		125,000	38	24	70
	1000	100,000	4.6	32	71
		75,000	48	31	80

Burst Strength, psi (computed using $S = \frac{PR}{T}$)	Processing Procedure
321,000 323,000	6-inch cylinders, forged, machined, and aged 3 hr at 900 F
324,000 321,000	6-inch cylinders, forged, machined, girth welded, and aged

These results are considered exceptional for a 250,000 psi yield-strength material.

Heat Treatment

The 18 Ni Co Mo (250) steel is heat treated by solution annealing at 1500 F ± 50 F for one hour per inch of section and maraging at 900 F ± 25 F for 3 hours. Because the M_f temperature is well above room temperature, the steel is completely martensitic at room temperature and refrigeration is not required. High strength can also be obtained by omitting the annealing treatment and simply maraging at 900 F for 3 hours, or by cold working between the annealing and maraging treatments. As shown in Table A-14, solution annealing results in a modest decrease (about 20,000 psi) in both unnotched and notched tensile strength. Cold working prior to aging increases yield and tensile strength but does not improve notched tensile strength.

Control of Composition

In the nickel-cobalt-molybdenum steels, high strength is believed to result from precipitation of a complex cobalt-molybdenum-titanium compound. Consequently, control of the contents of these elements is necessary. Increasing cobalt and molybdenum contents increases yield and tensile strength. For good toughness, however, it has been necessary to limit the molybdenum content to 5.1 per cent maximum. Titanium additions above 0.5 per cent were found to reduce toughness, and the maximum titanium content currently is restricted to this value. Aluminum also reduces toughness, and now is restricted to 0.10 per cent maximum. Increasing carbon up to 0.04 per cent was found to increase strength. Above 0.04 per cent, however, carbon reduces yield strength and notched tensile strength. Silicon and manganese increase strength but reduce ductility and toughness and are each restricted to 0.10 per cent maximum in the present composition.

A nickel content in the range of 17 to 19 per cent currently is specified. Higher nickel contents lower the M_s temperature, making refrigeration necessary to obtain complete transformation. Lower nickel contents reduce the notch strength of the alloy.

Welding

Sound, crack-free butt welds have been made on 18 Ni Co Mo (250) steel by coated-electrode, submerged-melt, and inert-gas-shielded processes using welding rod or filler metal of the same composition as the base plate. The International Nickel Company has reported the following properties in maraged butt welds produced in one-inch-thick, fully heat treated plate using coated electrodes:

0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction in Area, per cent	Notched Tensile Strength, ksi
222	250	5	17	250
229	260	8	20	315

Using the inert-gas-shielded tungsten arc process, yield strengths of about 230,000 psi and 5 per cent elongation have been obtained in specimens maraged at 900 F after welding. This represents a joint efficiency of about 90 per cent. In addition, this material showed excellent notch toughness with a notched-to-unnotched tensile ratio of about 1.2. Sheet, in thicknesses of 0.060 to 0.080 inch, has shown similar strength and notch toughness although tensile elongation has been low (2 to 4 per cent).

The attractive feature of this steel is that it can be welded, reportedly without difficulty, and requires only a simple maraging treatment to attain high strength and good toughness after welding.

Corrosion Resistance

The International Nickel Company reports that the 18 Ni Co Mo (250) steel shows good resistance to stress-corrosion cracking in the atmosphere at Bayonne, New Jersey, and in aerated artificial sea water. In the former medium, specimens stressed to their yield strength under three-point loading were not broken after one year. In the aerated artificial sea water, specimens were not broken after 180 days when loaded to their yield strength of 246,000 psi.

18 Ni Co Mo (300) Steel

Composition

The suggested composition for the best combination of yield strength (about 300,000 psi) and toughness is as follows:

Element	Per Cent
Nickel	18.0 - 19.0
Molybdenum	4.6 - 5.2
Cobalt	8.5 - 9.5
Titanium	0.5 - 0.8
Aluminum	0.10 added
Boron	0.003 added
Zirconium	0.02 added
Calcium	0.05 added
Carbon	0.01 - 0.03
Manganese	0.10 maximum
Phosphorus	0.01 maximum
Sulfur	0.01 maximum
Silicon	0.10 maximum

Physical Properties

The available physical-property data on the 18 Ni Co Mo (300) steel are as follows:

Density	7.93 g/c.c. or 0.289 lb/in.^{3} (determined on specimens in the A 1500 + M 900 condition)
Modulus of elasticity at room temperature	27.5 million psi

Mechanical Properties

This is the newest of the Mar-Aging steels and extensive property data are not yet available. The room-temperature tensile properties that are available are given in Table 11.

Data on properties at elevated temperatures and cryogenic temperatures are not available. Fatigue properties have not been reported.

Heat Treatment

This steel is heat treated in the same manner as the 18 Ni Co Mo (250) steel. Heat treatment may involve:

(1) Simply maraging at 900 F for 3 hours, or

(2) Solution annealing at 1500 F for 1 hour followed by maraging, or

(3) Solution annealing at 1500 F, cold working, and maraging.

TABLE 11. ROOM-TEMPERATURE TENSILE PROPERTIES OF 18 Ni Co Mo (300) STEEL

Condition	0.2 Per Cent Offset Yield Strength, ksi	Ultimate Tensile Strength, ksi	Elongation, per cent	Reduction of Area, per cent	Notched Tensile Strength, ksi
		Bar			
A 1500	120	150	18	75	-
A 1500	116	149	18	76	-
A 1500 + M 900	262	271	12	58	399
A 1500 + M 900	278	289	13	56	409
Hot rolled + M 900	281	285	11	58	422
Hot rolled + M 900	303	306	12	60	439
		Sheet			
A 1500 + M 900	280	290	2	-	223
A 1500 + M 900	309	310	2.5	-	275

As is the case with the 18 Ni Co Mo (250) steel, strength properties are improved by omitting the solution annealing treatment. Control of the maraging temperature is not especially critical; a ± 25 F variation is acceptable.

Control of Composition

The same compositional control employed for the 18 Ni Co Mo (250) steel should be employed for this steel, with the exception that a cobalt content of 8.5 to 9.5 per cent and a titanium content of 0.5 to 0.8 per cent are specified. To obtain the properties cited, careful control of these elements within this range is necessary.

Welding

Welding data on this steel have not been published. However, there are indications that the welding behavior will be about the same as that of the 18 Ni Co Mo (250) steel.

Corrosion Resistance

Corrosion data also are not yet available on the 18 Ni Co Mo (300) alloy.

PRESENT STATUS

As indicated earlier, these high-nickel steels are still in the development stage. Nevertheless, they show very considerable promise as high-strength structural materials. The alloys are presently capable of developing yield strengths of 240,000 to 320,000 psi with the excellent notch strength (K_T = 12) to yield strength ratios of 1.2 to 1.5. It has been optimistically estimated that yield strengths of approximately 400,000 psi will be developed by alloys of this class in the future.

At present, the following steel companies are known to be investigating the possibility of producing these steels on a commercial basis:

(1) Allegheny Ludlum Steel Corporation

(2) Republic Steel Corporation

(3) Carpenter Steel Company

(4) Special Metals Corporation

(5) Latrobe Steel Company

(6) Vanadium Alloy Steel Corporation

The International Nickel Company, of course, is continuing its research on this type of alloy. Together with Latrobe Steel Company, they are investigating the properties of the Mar-Aging steels in the form of structural shapes. Curtiss-Wright Corporation is also carrying out a program, under Air Force sponsorship, to study these alloys for potential application in rocket motor cases and aircraft structural components. Wyman-Gordon is cooperating with Curtiss-Wright.

Both Lyon, Incorporated, and The Budd Company are investigating these steels for high performance rocket motor cases under Army Ordnance contract. Republic Aviation has a contract with Watertown Arsenal on a missile case of lapped construction. In this program, one of the constructional materials under consideration is the 18 Ni Co Mo steel. Douglas Aircraft and Newport News Ship Building Company are working together on a program to evaluate the Mar-Aging steels for large boosters requiring material in plate thicknesses. It is also understood that Allison Division of General Motors Corporation has a contract to fabricate advanced models of the second-stage minuteman rocket motor case of the 18 Ni Co Mo (250) steel.

Convair, Fort Worth, is studying these steels for possible application as landing gears for the B 58 aircraft.

The Naval Research Laboratory has been studying the fracture properties of the Mar-Aging steels. Aerojet-General, Douglas, and Thiokol are investigating such factors as fracture strength, welding, and the mechanical properties of welded joints.

In addition, the Applications Laboratory, Wright-Patterson Air Force Base, is making every effort to encourage various procurement agencies within the Air Force to evaluate these steels for advanced missiles and aircraft.

Despite the extreme interest being shown, much is yet to be learned concerning these steels. Data are lacking on:

(1) Proper melting and processing controls

(2) Compressive properties

(3) Stress-strain diagrams both in tension and compression

(4) Elevated temperature properties

(5) Fatigue properties

(6) Welding characteristics

Of particular importance, is the lack of data on heavy sections of these steels, both plate and forged shapes.

Finally, it is presently understood that principal efforts are being directed toward the 18 Ni Co Mo steels because they have a high order of toughness and can be brought to ultrahigh-strength levels after welding by a simple heat treatment. Interest in the 25 Ni steel has dwindled greatly because of sensitivity to variations in composition and heat treatment, and also because of apparently inadequate notch toughness.

APPENDIX A

TABLE A-1. EFFECT OF SOLUTION TREATMENT ON PROPERTIES OF 25Ni STEEL - 0.076-IN. SHEET[a]

(Curtiss-Wright Data)

Annealing Temperature, F	Annealing Time,[b] min	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, 1000 psi	0.2 Per Cent Offset Yield Strength, 1000 psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
				Longitudinal			
1600	60	800	49	237.5	220	8.5	34.0
		850	51	248	235	5.5	26.0
		900	49.5	251	234	5.8	36.0
		950	50	247	230.5	5.0	20.5
1500	15	800	49	245	225.5	9.0	31.0
		850	50	256	244	5.0	23.0
		900	51.5	262	238	7.5	46.0
		950	50.5	249	240	6.5	26.0
1500	60 (Bar stock — INCO data)	850	--	279	265	12.0	52.0
		900	--	279	268	12.0	51.0
				Transverse			
1600	60	800	49	244	221.5	8.0	35.5
		850	51	251.5	238	5.5	24.0
		900	49.5	259	241.5	7.0	36.0
		950	50	254	241	6.0	24.0
1500	15	800	49	248	226	8.0	34.0
		850	50	259	234	5.0	29.0
		900	51.5	268	248	7.0	41.0
		950	50.5	261	242	4.0	13.0

(a) Allegheny Ludlum Consutrode Heat No. 23223: Fe - 25.33Ni - 1.37Ti - 0.20Al - 0.54Cb + 0.006C - 0.12Mn - 0.17Si - 0.008P - 0.002S.

(b) Heat treatment: solutioned as indicated, 1300 F for 4 hr, refrigerated in Dry Ice for 16 hr, aged at indicated temperature for 1 hr.

TABLE A-2. EFFECT OF BORON-ZIRCONIUM TREATMENT ON TENSILE PROPERTIES OF THE 25Ni STEEL

(Inco Data)

Composition, wt%(a)						Heat Treatment			Addition		Notched Tensile Strength, psi	Per Cent Increase in Notched Tensile Strength	Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent	Reduction in Area, per cent
Ni	Al	Ti	Cb	Mn	Si	Tempera-ture, F	Time, hr	Cool(b)	Per Cent B	Per Cent Zr						
24.9	0.26	1.70	0.47	0.17	0.15	1500	1	A	0	0	153,000	--	233,000	287,000	11	31
24.6	0.29	1.70	0.45	0.18	0.18	1300	4	A	.002	.02	220,000	43	231,000	284,000	10	32
24.9	0.28	1.69	0.45	0.18	0.17	950	1	A	.005	.02	214,000	40	224,000	286,000	12	43
						1500	1	A	0	0	152,000	--	259,000	276,000	9	32
						1300	30	A	.002	.02	204,000	35	259,000	274,000	11	38
						950	1	A	.005	.02	235,000	55	256,000	274,000	10	40
						1500	1	A	0	0	232,000	--	251,000	293,000	11	28
						1300	4	B	.002	.02	305,000	31	249,000	285,000	14	43
						850	1	A	.005	.02	260,000	12	248,000	286,000	13	42
						300	16	A								
24.9	0.26	1.66	0.35	0.11	0.10	1500	1	A	0	0	195,000	--	237,000	289,000	11	26
24.9	0.26	1.59	0.44	0.15	0.12	1300	4	B	.002	.02	225,000	15	236,000	285,000	11	30
25.0	0.34	1.58	0.44	0.17	0.15	850	1	A	.005	.02	208,000	7	227,000	287,000	11	26
						300	16	A								
24.8	0.21	1.54	0.40	0.03	0.12	1500	1	A	0	0	243,000	--	234,000	256,000	14	54
24.8	0.26	1.60	0.44	0.03	0.13	1300	4	B	.002	.02	288,000	19	248,000	273,000	15	50
24.7	0.17	1.60	0.45	0.02	0.07	850	1	A	.003	.02	314,000	29	258,000	272,000	12	40
24.8	0.17	1.58	0.45	0.03	0.09	300	16	A	.003	.02	301,000	24				
25.1	0.21	1.48	0.41	0.03	0.11				.005	.02	321,000	32	237,000	254,000	13	30
24.9	0.11	1.60	0.46	0.05	0.07	1500	1	A	.003	.02	309,000	27	248,000	270,000	13	38
25.2	0.12	1.65	0.49	0.05	0.08	1300	4	B	.003	.02	283,000	16	251,000	283,000	15	48
25.0	0.11	1.60	0.47	0.05	0.08	850	1	A	.003	.02	286,000	17	251,000	276,000	15	55

(a) Ca - .01-.028.
S - .005-.008.
P - .004-.006.
C - .009-.06.

(b) A = air cool to room temperature; B = air cool to 220 F, water cooled to 55 F.

TABLE A-3. LONGITUDINAL TENSILE PROPERTIES OF THE 1.37Ti-25Ni STEEL MARAGED FOR 1 HOUR - 0.076-IN. SHEET[a]

(Curtiss-Wright Data)

Per Cent Reduction	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
0[b]	800	49	237,500	220,000	8.5	34.0
	850	51	248,000	235,000	5.5	26.0
	900	49.5	251,000	234,000	5.8	36.0
	950	50	247,000	230,500	5.0	20.5
20[c]	800	46.5	221,500	201,300	9.0	35.0
	850	50	252,000	237,000	7.0	32.0
	900	51.5	259,000	245,000	7.0	31.5
	950	50.5	251,000	243,000	6.0	31.0
30[c]	800	47.5	234,000	216,000	8.5	29.5
	850	51	261,000	245,000	7.0	31.0
	900	52.5	264,500	253,000	6.0	36.0
	950	50	250,000	240,000	5.5	32.5
40[c]	800	47	228,000	209,000	8.5	35.0
	850	51	263,000	251,000	7.0	32.0
	900	52.5	267,500	257,000	5.5	36.0
	950	52	261,000	242,500	6.0	32.5
50[c]	800	49.5	238,000	223,000	7.0	30.0
	850	52	268,500	259,000	5.5	29.5
	900	53	271,500	262,000	5.5	33.5
	950	51.5	263,500	251,500	5.5	31.5
70[c]	800	51.5	256,000	235,000	5.5	33.0
	850	52.5	278,000	264,000	5.5	27.5
	900	53.5	282,000	268,000	5.5	33.5
	950	52.5	270,000	258,000	6.0	34.5
90[c]	800	52	285,500	266,500	5.5	16.0
	850	53.5	301,500	292,000	5.0	32.5
	900	54	296,500	287,500	4.5	25.0
	950	53	280,000	271,500	4.0	34.0

(a) Allegheny Ludlum Consutrode Heat No. 23223: 25.33Ni-1.37Ti-0.20Al-0.54Cb-0.17Si-0.12Mn-0.008P-0.002S-0.006C, balance Fe.

(b) 1600 F for 1 hr, 1300 F for 4 hr, refrigerated in Dry Ice for 16 hr, aged 1 hr at temperature.

(c) 1600 F for 1 hr, cold worked, refrigerated in Dry Ice for 16 hr, aged 1 hr at temperature.

TABLE A-4. TRANSVERSE TENSILE PROPERTIES OF THE 1.37Ti-25Ni STEEL MARAGED FOR 1 HOUR - 0.076-IN. SHEET[(a)]

(Curtiss-Wright Data)

Per Cent Reduction	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
0[(b)]	800	49	244,000	221,500	8.0	34.5
	850	51	251,500	238,000	5.5	24.0
	900	49.5	259,000	241,500	7.0	36.0
	950	50	254,000	241,000	6.0	24.0
20[(c)]	800	46.5	233,000	204,500	8.0	27.0
	850	50	263,000	246,000	7.0	34.0
	900	51.5	269,000	257,000	7.0	34.5
	950	50.5	262,500	249,000	5.0	29.5
30[(c)]	800	47.5	238,000	212,000	8.0	26.5
	850	51	265,500	253,500	6.5	27.0
	900	52.5	268,500	254,500	5.5	26.5
	950	50	263,500	249,000	5.5	20.5
40[(c)]	800	47	235,000	212,000	7.5	31.0
	850	51	275,500	259,500	7.5	27.5
	900	52.5	276,000	263,000	5.5	25.0
	950	52	269,000	255,500	5.5	31.0
50[(c)]	800	49.5	247,000	224,000	6.0	25.5
	850	52	269,500	251,000	5.0	30.0
	900	53	277,500	262,500	5.5	24.5
	950	51.5	270,500	255,000	4.5	18.0
70[(c)]	800	51.5	261,500	241,500	4.0	28.0
	850	52.5	288,500	274,500	5.0	33.0
	900	53.5	291,000	276,000	4.0	23.0
	950	52.5	283,000	267,000	4.5	27.5
90[(c)]	800	52	302,500	287,000	4.0	7.0
	850	53.5	321,500	315,000	3.0	2.7
	900	54	313,000	307,500	2.0	1.5
	950	53	295,500	283,000	3.0	5.5

(a) Allegheny Ludlum Consutrode Heat No. 23223: 25.33Ni-1.37Ti-0.20Al-0.54Cb-0.17Si-0.12Mn-0.008P-0.002S-0.006C, balance Fe.
(b) 1600 F for 1 hr, 1300 F for 4 hr, refrigerated in Dry Ice for 16 hr, aged 1 hr at temperature.
(c) 1600 F for 1 hr, cold worked, refrigerated in Dry Ice for 16 hr, aged 1 hr at temperature.

TABLE A-5. LONGITUDINAL TENSILE PROPERTIES OF 1.37Ti-25Ni STEEL MARAGED FOR 4 HOURS - 0.076-IN. SHEET[a]

(Curtiss-Wright Data)

Per Cent Reduction	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
0[b]	800	51	252,000	234,000	5	20
	850	52	263,000	242,000	6	28
	900	50	252,000	232,000	5	23
	950	47.5	243,000	217,000	8	21

(a) Allegheny-Ludlum Consutrode Heat No. 23223 (see Table A-1 for composition).
(b) 1600 F for 1 hr, 1300 F for 4 hr, refrigerated in Dry Ice for 16 hr, aged 4 hr at temperature.

TABLE A-6. LONGITUDINAL TENSILE PROPERTIES OF THE 1.73Ti-25Ni STEEL - 0.076-IN. SHEET[a]

(Curtiss-Wright Data)

Per Cent Reduction	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation	Reduction in Area, per cent
0[b]	800	--	255,000	230,600	7.7	33.1
	850	--	260,300	238,000	8.3	35.2
	900	--	259,300	245,000	7.2	30.0
	950	--	249,000	220,000	8.3	30.6
20[c]	800	50	258,000	249,000	5.2	31.0
	850	52.5	278,000	265,000	6.3	35.0
	900	53.5	283,300	272,000	4.5	33.0
	950	53	275,000	260,500	4.4	34.5
30[c]	800	50.5	264,500	252,500	6.0	35.5
	850	53	283,300	270,000	4.5	26.6
	900	53.5	289,000	279,000	4.8	34.3
	950	53	279,500	263,000	4.8	40.0
40[c]	800	51.5	270,000	257,000	6.4	38.0
	850	53.5	280,700	275,300	4.0	35.3
	900	54	291,600	283,600	3.8	34.3
	950	53.5	287,000	272,500	4.0	42.0
50[c]	800	52	275,000	268,000	5.5	37.0
	850	54	288,000	278,000	5.6	33.3
	900	54	291,600	284,000	4.0	22.6
	950	53	287,000	263,500	4.0	34.5
70[c]	800	53	288,500	279,000	5.0	22.0
	850	55	301,800	294,300	4.6	22.6
	900	55	312,300	304,600	3.6	20.0
	950	54	286,500	278,500	3.0	20.5

(a) Kelsey-Hayes Vacuum Induction Heat No. 52594: 24.6Ni-1.73Ti-0.22Al-0.38Cb-0.10Mn-0.10Si-0.03C, balance Fe.
(b) Heat treatment: 1600 F for 1 hr, 1300 F for 4 hr, refrigerated in liquid nitrogen, aged 1 hr at temperature.
(c) Heat treatment: 1600 F for 1 hr, cold worked, refrigerated in liquid nitrogen, aged 1 hr at temperature.

TABLE A-8. FRACTURE TOUGHNESS OF ANNEALED 25Ni STEEL WITH 1.37Ti

(Inco Data)

Aging Treatment[a]	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Per Cent Elongation	G_c, in -lb/in.^{2}	K_c, psi$\sqrt{in.}$	σ_n, psi
1300 F, 4 hr, 800 F, hr	212,500	240,500	5.75	1512	213,000	209,000
1300 F, 4 hr, 850 F, hr	234,000	255,000	4.0	634	137,000	150,000
1300 F, 4 hr, 900 F, hr	247,500	267,000	2.85	369	105,000	118,000

(a) Material solution annealed at 1500 F for 40 min prior to ausaging and refrigerated; -100 F for 16 hr after ausaging.

TABLE A-9. FRACTURE TOUGHNESS OF COLD-WORKED 25Ni STEEL ALLOY WITH 1.37Ti

(Inco Data)

Per Cent Reduction	Aging Treatment[(a)]	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Per Cent Elongation	G_c, in-lb/in.^{2}	K_c, psi $\sqrt{\text{in.}}$	σ_n, psi
			Transverse				
25	800 F, 1 hr	261,250	278,500	4.0	1204	190,000	205,000
	850 F, 1 hr	259,000	282,000	--	1118	183,000	199,000
	900 F, 1 hr	260,500	279,250	4.0	1285	197,000	212,000
50	800 F, 1 hr	269,500	290,500	4.5	866	161,000	179,000
	850 F, 1 hr	277,000	293,500	4.25	474	118,000	131,000
	900 F, 1 hr	268,500	293,500	4.35	516	124,000	136,000
75	800 F, 1 hr	287,750	300,000	3.0	499	122,000	134,000
	850 F, 1 hr	304,250	318,000	3.0	358	104,000	115,000
	900 F, 1 hr	304,000	314,500	2.0	303	96,000	106,000
			Longitudinal				
25	800 F, 1 hr	254,500	268,000	4.0	1383	202,000	211,000
75	800 F, 1 hr	--	241,500	--	575	130,000	142,000

(a) Material solution annealed at 1500 F for 1 hr; refrigerated -100 F for 16 hr after cold working.

TABLE A-10. ROOM-TEMPERATURE TENSILE TEST RESULTS FOR AIR AND VACUUM MELTS OF 20Ni STEEL

(Inco Data)

Melting Method	Composition, wt% Al	Ti	Cb	Heat Treatment	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Per Cent Elongation	Reduction in Area, per cent	Notched Tensile Strength, psi	NTS/YS	NTS/UTS
Air	0.16	1.32	0.17	1500/1 + 900/1	238,000	245,000	11	51	353,100	1.48	1.44
				1500/1 + refrig + 900/1	236,000	247,000	11	47.5	351,700	1.48	1.47
				900/1	245,000	250,000	10	45.5	347,000	1.42	1.39
				1500/1 + 50% CW + 900/1	254,500	259,500	10	47.5	354,100	1.39	1.36
Air	0.19	1.60	0.35	1500/1 + 900/1	270,000	280,000	10	37.5	283,300	1.05	1.01
				1500/1 + refrig + 900/1	268,900	278,900	10	45.5	317,800	1.18	1.14
				900/1	274,600	280,300	10	45.5	295,500	1.08	1.05
				1500/1 + 50% CW + 900/1	287,500	292,600	8	31.5	308,775	1.07	1.05
Air	0.21	1.90	0.28	1500/1 + 900/1	290,500	298,600	7	28.5	225,900	0.78	0.76
				1500/1 + refrig + 900/1	286,300	296,400	10	40.5	227,300	0.79	0.77
				900/1	291,200	301,000	10	45	264,200	0.91	0.88
				1500/1 + 50% CW + 900/1	182,200(a)	192,300	8	34	269,900	1.48	1.40
Air	0.12	1.41	0.25	1500/1 + 900/1	252,500	259,400	9	33	362,200	1.43	1.40
				1500/1 + refrig + 900/1	254,600	260,700	9	39	360,200	1.41	1.38
				900/1	253,000	262,200	10	43.5	349,900	1.38	1.33
				1500/1 + 50% CW + 900/1	266,700	269,700	8	34	307,700	1.15	1.14
Vacuum	0.22	1.55	0.40	1500/1 + 900/1	261,100	274,300	9	34.5	279,000	1.07	1.02
				1500/1 + refrig + 900/1	262,200	276,400	10	40.5	297,500	1.13	1.08
				900/1	277,100	288,200	9	37.5	308,800	1.11	1.07
				1500/1 + 50% CW + 900/1	273,100	282,100	11	52.5	299,150	1.09	1.06
Vacuum	0.21	1.80	0.43	1500/1 + 900/1	266,100	280,200	10	37	238,600	0.90	0.85
				1500/1 + refrig + 900/1	275,500	289,800	8	30.5	235,900	0.86	0.81
				900/1	281,600	293,900	8	35.5	310,200	1.10	1.06
				1500/1 + 50% CW + 900/1	291,500	300,600	6	21	357,100	1.23	1.19
Vacuum	0.21	1.57	0.40	1500/1 + 900/1	262,600	274,700	10	42.5	312,500	1.19	1.14
				1500/1 + refrig + 900/1	259,800	274,700	10	45.5	304,000	1.17	1.11
				900/1	276,600	286,900	13	57	361,200	1.31	1.26
				1500/1 + 50% CW + 900/1	280,300	286,900	8	37	294,275	1.05	1.03
Vacuum	0.13	1.37	0.32	1500/1 + 900/1	245,900	256,100	11	45.5	369,300	1.5	1.44
				1500/1 + refrig + 900/1	243,900	255,100	8(a)	53.5	373,900	1.53	1.47
				900/1	257,100	266,100	13	55.5	372,900	1.45	1.40
				1500/1 + 50% CW + 900/1	262,800	268,400	12	57	389,500	1.48	1.45

(a) Broke at gage mark.

TABLE A-11. TRANSVERSE TENSILE PROPERTIES OF 20 Ni STEEL – 0.076-IN. SHEET[a]

Per Cent Reduction	Aging Temperature, F	Aging Time, hr	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
0[b]	800	1	42	184,000	170,000	5	6
		2	46.5	188,000	182,100	1.5	4
		4	47	205,500	202,000	2.5	2
	850	1	46.5	228,000	216,000	4	9
		2	47	239,000	223,000	6	31
		4	47.5	244,000	225,500	6	28
	900	1	49.5	242,000	220,000	4	23
		2	48	244,000	230,000	5	24
		4	50	253,000	234,000	6	30
	950	1	47.5	246,000	230,000	4	24
		2	49	240,000	228,000	6	30
		4	47	235,000	220,000	6	29
20[c]	800	1	45	210,000	201,000	5	9
		2	46	214,000	206,000	2	6
		4	48.5	234,000	226,000	3	6
	850	1	48	247,500	236,000	5	2
		2	47	249,000	235,000	6	33
		4	50	253,000	240,000	5	23
	900	1	50	255,000	240,000	6	26
		2	49.5	256,000	246,000	4	18
		4	49	251,000	237,000	7	34
	950	1	49.5	254,000	243,000	5	32
		2	49	253,000	242,000	6	30
		4	49	250,000	234,000	6	31
30[c]	800	1	45.5	222,000	208,000	6	18
		2	47.5	232,000	216,000	2.5	8
		4	48	247,000	235,000	4	5
	850	1	49.5	253,000	241,500	6	23
		2	48	257,000	240,000	4	21
		4	49	260,000	243,000	4	20
	900	1	49	275,000	258,000	5	20
		2	51	264,000	249,000	5	35
		4	49.5	251,000	243,000	5	34
	950	1	50	259,000	247,000	5	27
		2	49.5	257,000	247,000	6	36
		4	48	254,000	239,000	5	32
40[c]	800	1	45	220,000	206,000	5	18
		2	47	234,000	216,000	1.5	7
		4	47.5	248,000	236,000	4	18
	850	1	49.5	252,000	243,000	6	22
		2	48	258,000	244,000	4	25.5
		4	48.5	260,000	244,000	5	22
	900	1	49.5	261,000	239,000	4	25
		2	50	263,000	252,000	5	20
		4	49.5	261,000	253,000	6	31
	950	1	48	259,000	249,000	5	27
		2	49	258,000	247,000	6	27
		4	48	253,000	241,000	4	31
50[c]	800	1	45	233,000	219,000	6	14
		2	48	242,000	226,000	1	5
		4	49	250,000	238,000	3	7
	850	1	48.5	261,000	250,500	5	19
		2	50	265,000	249,000	3	16.5
		4	50	268,000	253,500	4	16

TABLE A-11. (Continued)

Per Cent Reduction	Aging Temperature, F	Aging Time, hr	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
50(c)	900	1	50	270,000	254,000	5	21
		2	50.5	271,000	259,000	5	25
		4	50	264,000	252,000	6	32
	950	1	51.5	268,000	251,000	5	24
		2	50	262,000	249,000	5	20
		4	49.5	259,000	242,000	4	20
70(c)	800	1	50.5	264,000	254,000	5	12
		2	50	276,000	264,000	2.5	16
		4	50	284,000	276,000	5	18
	850	1	51.5	291,000	281,000	4	10
		2	51	288,000	277,000	3	15.5
		4	51.5	289,000	280,000	2.5	14
	900	1	52	292,000	280,000	2	10
		2	51	286,000	278,000	4	16
		4	49	273,000	259,000	4	13
	950	1	51	282,000	271,000	4	13
		2	51	276,000	265,000	3.5	18
		4	49	266,000	259,000	3	19
90(c)	800	1	51.5	297,000	291,000	5.5	0
		2	52.5	292,000	282,000	1	5
		4	52	310,000	304,000	3	0
	850	1	52	314,000	310,500	3	3
		2	51	297,000	296,000	2	8.5
		4	51	310,000	300,000	0.5	3
	900	1	52	258,000	(d)	0	0
		2	51	287,000	(d)	0	2
		4	50	299,000	290,000	2	3
	950	1	50	295,000	288,000	2	2
		2	51	285,000	272,000	3	7
		4	50	270,000	257,000	3	9

(a) Allegheny Ludlum Consutrode Melted Heat No. 23222: 20.04Ni-1.27Ti-0.22Al-0.52Cb-0.15Si-0.11Mn-0.007P-0.002S-0.007C, balance Fe.
(b) 1600 for 1 hr, refrigerated in Dry Ice for 16 hr, aged as indicated.
(c) 1600 for 1 hr, cold worked as indicated, aged as indicated.
(d) Failed in elastic region.

TABLE A-12. EFFECT OF SOLUTION TREATMENT ON PROPERTIES OF 20Ni STEEL – 0.076-IN. SHEET[(a)]

Solution Temperature, F	Solution Time, min	Aging Temperature, F	Rockwell C Hardness	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Per Cent Elongation in 1 Inch	Reduction in Area, per cent
				Longitudinal			
1600	60	800	47	216,000	204,000	4	4
		850	46.5	235,000	220,500	4	24
		900	49.5	240,000	224,000	4	29
		950	47.5	232,000	214,000	6	31
1500	15	800	48.5	237,000	214,000	8	38
		850	49.5	245,000	222,000	6	50
		900	49.5	248,000	231,000	6	49
		950	48	234,000	219,000	8	57
				Transverse			
1600	60	800	47	205,500	202,000	3	2
		850	46.5	244,000	225,500	6	28
		900	49.5	253,000	234,000	6	30
		950	47.5	235,000	220,000	6	29
1500	15	800	48.5	244,000	223,000	8	39
		850	49.5	256,000	238,000	7	46
		900	49.5	258,000	240,000	6	43
		950	48	240,000	225,000	7	51

(a) Allegheny Ludlum Consutrode Heat No. 23222: Fe-20.04Ni-1.27Ti-0.22Al-0.52Cb-0.007C-0.11Mn-0.15Si-0.007P-0.002S.
Heat treatment: Solutioned as indicated, refrigerated in Dry Ice for 16 hr, aged at temperature for 4 hr.

TABLE A-13. FRACTURE TOUGHNESS OF 20Ni STEEL

(Inco Data)

Per Cent Reduction	Aging Treatment[a]	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Per Cent Elongation	G_c, in-lb/in^2	K_c, psi $\sqrt{in.}$	σ_n, psi
			Transverse				
0[a]	850 F, 1 hr	229,500	243,750	5.0	3130	300,000	260,000
	900 F, 1 hr	247,000	256,750	4.25	2217	257,000	248,000
	950 F, 1 hr	247,750	256,750	4.0	3131	298,000	280,000
50[b]	850 F, 1 hr	263,250	271,000	3.5	373	105,000	116,000
	900 F, 1 hr	278,000	285,250	3.25	386	107,000	118,000
	950 F, 1 hr	274,000	280,500	3.5	638	137,000	149,000
			Longitudinal				
0[a]	850 F, 1 hr	227,500	242,000	5.75	3245	308,000	271,000
	900 F, 1 hr	243,250	253,000	4.75	2552	276,000	256,000
	950 F, 1 hr	243,750	252,500	4.0	2928	286,000	272,000
50[b]	850 F, 1 hr	259,000	262,750	4.0	1156	185,000	193,000
	900 F, 1 hr	273,000	272,000	4.0	1405	205,000	214,000
	950 F, 1 hr	258,000	262,250	4.0	2391	246,000	258,000

(a) Solution annealed 1 hr at 1600 F, refrigerated in Dry Ice for 16 hr, aged as indicated.
(b) Solution annealed 1 hr at 1600 F, cold worked, aged as indicated.

TABLE A-14. BAR PROPERTIES OF 18Ni-Co-Mo (250) STEEL

(Inco Data)

Heat	Composition, wt%(a) Ni	Co	Mo	Ti	C	Annealing Tempera-ture, F	Annealing Rockwell C Hardness	Cold Work, per cent	Age Tempera-ture, F	Age Hr	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent	Reduction in Area, per cent	Round Notch (K_t = 12) Tensile 0.3-In.-Diam Bar, psi	NTS/TS
29924	18.8	7.5	4.8	0.43	0.013	1500	29	--	--	--	116,000	146,000	19	72	--	--
	Vacuum melt					1500	--	--	900	3	247,000	259,000	12	56	395,000	1.52
						--	--	--	900	3	267,000	273,000	12	58	415,000	1.52
29939	(18.5)	(7.5)	(4.9)	(0.6)	(0.01)	1500	32	--	--	--	115,000	147,000	17	76	--	--
						1500	--	--	900	3	275,000	285,000	12	58	426,000	1.50
	Vacuum melt					--	--	--	900	3	295,000	29/,000	12	60	449,000	1.51
						1500	--	50	900	3	295,000	301,000	13	58	427,000	1.42

(a) Parentheses indicate intended composition.

TABLE A-15. TENSILE AND FRACTURE TOUGHNESS PROPERTIES OF VACUUM-MELTED COLD-WORKED 18Ni-Co-Mo (250) STEEL

(Inco Data)

Heat	Treatment	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent	σ_a, psi	σ_{NS}, psi	K_c, psi $\sqrt{in.}$	G_c, in-lb/in.^{2}	β	Critical Crack Length, in.	Test Specimen Width, in.	Test Specimen Thickness, in.
29924(a)	1/1500 + 50% CW + 3/900	286,000	289,000	3.5	302,000	265,000	212,000	1960	7.1	0.18	1	0.078
					272,000	224,000	246,000	2290	9.7	0.24	2	0.077
29939(b)	1/1500 + 50% CW + 3/900	306,000	308,000	3.0	316,000	276,000	244,000	1825	8.7	0.17	1	0.061
					217,000	211,000	181,000	1195	4.5	0.11	2	0.078

(a) Contains 0.43Ti by analysis.
(b) Contains a nominal 0.6Ti.

TABLE A-16. ELEVATED TEMPERATURE PROPERTIES OF A LABORATORY MELT OF 18Ni-Co-Mo(250) STEEL[a]

(Inco Data)

Test Temperature, F	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent in 1 inch	Reduction in Area, per cent	Stress-Rupture Properties			
					Stress, psi	Life, hr	Elongation, per cent	Reduction in Area, per cent
800	209,000	221,000	12	56	175,000	38	13	51
					150,000	561	13	59
900	184,000	98,000	19	66	150,000	6.7	17	63
					125,000	38	24	70
1000	138,000	154,000	24	74	100,000	4.6	32	71
					75,000	48	31	80

(a) Composition: 19.5Ni-7Co-4.9Mo-0.41Ti, balance Fe.
Heat treatment: annealed 1500 F for 1 hr, aged 900 F for 3 hr.

TABLE A-17. TRANSVERSE WELD TENSILE PROPERTIES OF GAS, METAL-ARC WELDED 1/2-INCH-THICK 250,000-PSI NOMINAL YIELD STRENGTH 18Ni PLATE[a,b]

Filler Wire Heat No.[c]	Filler Wire Composition Ni	Co	Mo	Ti	Weld No.	Age Tempera-ture, F	Hr	Weld Rockwell C Hardness	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent	Reduction in Area, per cent	Location of Fracture	Round NTS, psi	NTS/TS
29679-2	18	8	4.7	0.57	10939	850	3	43.7	217,000	230,000	10	41.5	Plate	294,000	1.28[d]
29679-2	18	8	4.7	0.57	10939	900	3	45.5	232,000	240,000	5	32	Weld	281,000	1.17
30633-1	15.8	7.9	5.0	0.42	10789	900	1	41.5	--	--	--	--	--	289,000	--
30633-1	15.8	7.9	5.0	0.42	10789	900	3	44.8	--	--	--	--	--	291,000	--
30633-1	15.8	7.9	5.0	0.42	10789	950	1	44.8	--	--	--	--	--	292,000	--
30633-2	16	7.95	5.0	0.40	10790	850	1	41.2	--	--	--	--	--	300,000	--
30633-2	16	7.95	5.0	0.40	10790	850	3	41.3	--	--	--	--	--	299,000	--
30633-2	16	7.95	5.0	0.40	10790	900	1	40.3	210,000	223,000	12	48	Plate	312,000	1.4[d]
30633-2	16	7.95	5.0	0.40	10790	900	3	42	227,000	235,000	12	49.5	Plate	275,000	1.17[d]

(a) Base plate - Heat 84625: Fe-18.7Ni-7.87Co-4.59Mo-0.24Ti-0.085Al-0.026C-0.010Mn-0.064Si-0.008P-0.010S-0.01Zr-0.003B (added).
(b) Smooth bar spec. - 0.252-in. diam.
Notched bar spec. - 0.3-in. diam.
(c) 0.062-in. diam.
(d) Calculated on basis of plate tensile strength.

TABLE A-18. MECHANICAL AND FRACTURE TOUGHNESS PROPERTIES OF TIG WELDED 250,000-PSI NOMINAL YIELD STRENGTH 18Ni SHEET - 0.080-IN. SHEET[(a, b)]

0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Net Fracture Stress, N, psi	K_c, psi $\sqrt{\text{in.}}$	G_c, in.-lb/in.^{2}	Critical Crack Length, in.	β
227,000	230,000	246,000	>178,000	>1150	>0.19	>9.7

(a) Base metal and filler wire - Heat No. 84625 (see Table A-16).
(b) Heat treated at 900 F for 3 hr.

TABLE A-19. BAR PROPERTIES OF THE 18Ni-Co-Mo (300) STEEL

(Inco Data)

Heat	Composition, wt%[a] Ni	Co	Mo	Ti	C	Annealing Tempera-ture, F	Annealing Rockwell C Hardness	Cold Work, per cent	Age Tempera-ture, F	Age Hr	0.2 Per Cent Offset Yield Strength, psi	Ultimate Tensile Strength, psi	Elongation, per cent	Reduction in Area, per cent	Round Notch (K_t = 12) Tensile 0.3-In.-Diam Bar, psi	NTS/TS
29934	18.6	8.8	4.9	0.42	0.005	1500	28	--	--	--	120,000	150,000	18	75	--	--
	Vacuum melt					1500	--	--	900	3	262,000	271,000	12	58	399,000	1.47
						--	--	--	900	3	281,000	285,000	11	58	422,000	1.48
29942	(18.5)	(9.)	(4.9)	(0.4)	(0.01)	1500	32	--	--	--	116,000	149,000	18	76	--	--
						1500	--	--	900	3	278,000	289,000	13	56	409,000	1.42
	Vacuum melt					--	--	--	900	3	303,000	306,000	12	60	439,000	1.44
						1500	--	50	900	3	288,000	294,000	14	58	447,000	1.52

(a) Parentheses indicate intended composition.

TABLE A-20. TENSILE AND FRACTURE TOUGHNESS PROPERTIES OF VACUUM-MELTED COLD-WORKED 18Ni-Co-Mo STEEL

(Inco Data)

Heat	Treatment	0.2 Per Cent Offset Yield Strength, 1,000 psi	Ultimate Tensile Strength, psi	Elongation, per cent	σ_a, psi	σ_{ns}, psi	K_c, psi$\sqrt{in.}$	G_c, in-lb/in.^{2}	β	Critical Crack Length, in.	Test Specimen Width, in.	Test Specimen Thickness, in.
29934[a]	1/1500 + 50% CW + 3/900	300,000	301,000	3.5	271,000	258,000	172,000	1116	4.9	0.11	1	0.068
					213,000	205,000	178,000	1200	5.2	0.11	2	0.068
29942[b]	1/1500 + 50% CW + 3/900	309,000	310,000	2.5	275,000	263,000	174,000	1100	7.6	0.10	1	0.042
					202,000	197,000	180,000	1178	8.8	0.11	2	0.039
29942[b]	1/1500 + 70% CW + 3/900	326,000	326,000	2.0	247,000	239,000	149,000	813	4.2	0.07	1	0.050
					191,000	183,000	156,000	888	4.7	0.08	2	0.050

(a) Actual composition: 18.6Ni-8.8Co-4.9Mo-0.42Ti-0.005 C.
(b) Intended composition: 18.5Ni-9.0Co-4.9Mo-0.4Ti-0.01C.

LIST OF DMIC MEMORANDA ISSUED

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
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Copies of the technical memoranda listed below may be obtained from DMIC at no cost by Government agencies and by Government contractors, subcontractors, and their suppliers. Others may obtain copies from the Office of Technical Services, Department of Commerce, Washington 25, D. C.

A list of DMIC Memoranda 1-117 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
118	Review of Recent Developments in the Metallurgy of High-Strength Steels, July 21, 1961, (AD 259986 $0.50)
119	The Emittance of Iron, Nickel, Cobalt and Their Alloys, July 25, 1961, (AD 261336 $2.25)
120	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, July 31, 1961, (AD 261293 $0.50)
121	Fabricating and Machining Practices for the All-Beta Titanium Alloy, August 3, 1961, (AD 262496 $0.50)
122	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, August 4, 1961, (AD 261292 $0.50)
123	Review of Recent Developments in the Technology of Beryllium, August 18, 1961, (AD 262497 $0.50)
124	Investigation of Delayed-Cracking Phenomenon in Hydrogenated Unalloyed Titanium, August 30, 1961, (AD 263164 $0.50)
125	Review of Recent Developments in Metals Joining, September 1, 1961, (AD 262905 $0.50)
126	A Review of Recent Developments in Titanium and Titanium Alloy Technology, September 15, 1961, (AD 263167 $0.50)
127	Review of Recent Developments in the Technology of Tungsten, September 22, 1961, (AD 263888 $0.50)
128	Review of Recent Developments in the Evaluation of Special Metal Properties, September 27, 1961, (AD 263994 $0.50)
129	Review of Recent Developments in the Technology of Molybdenum and Molybdenum-Base Alloys, October 6, 1961, (AD 264291 $0.50)
130	Review of Recent Developments in the Technology of Columbium and Tantalum, October 10, 1961, (AD 264983 $0.50)
131	Review of Recent Developments in the Technology of High-Strength Stainless Steels, October 13, 1961, (AD 264984 $0.50)
132	Review of Recent Developments in the Metallurgy of High-Strength Steels, October 20, 1961, (AD 265135 $0.50)
133	Titanium in Aerospace Applications, October 24, 1961, (AD 266927 $1.50)
134	Machining of Superalloys and Refractory Metals, October 27, 1961, (AD 268081 $1.00)
135	Review of Recent Developments in the Technology of Nickel-Base and Cobalt-Base Alloys, October 31, 1961, (AD 266004 $0.50)
136	Fabrication of Tungsten for Solid-Propellant Rocket Nozzles, November 2, 1961, (AD 268311 $0.75)
137	Review of Recent Developments on Oxidation-Resistant Coatings for Refractory Metals, November 8, 1961, (AD 266469 $0.50)
138	Review of Recent Developments in the Technology of Beryllium, November 16, 1961, (AD 267079 $0.50)
139	Review of Recent Developments in the Technology of Tungsten, November 24, 1961, (AD 268082 $0.50)

LIST OF DMIC MEMORANDA ISSUED
(Continued)

DMIC Memorandum Number	Title
140	Review of Recent Developments in Metals Joining, December 6, 1961, (AD 268312 $0.50)
141	The Emittance of Chromium, Columbium, Molybdenum, Tantalum, and Tungsten, December 10, 1961, (AD 269784 $1.25)
142	Effects of Moderately High Strain Rates on the Tensile Properties of Metals, December 18, 1961, (AD 270167 $1.00)
143	Notes on the Forging of Refractory Metals, December 21, 1961, (AD 271030 $1.50)
144	Review of Recent Developments in Titanium Alloy Technology, December 29, 1961, (AD 269209 $0.50)
145	The Use of Nickel-Base Alloys in the Rotating Parts of Gas Turbines for Aerospace Applications, January 11, 1962, (AD 271174 $0.75)
146	Magnesium-Lithium Alloys - A Review of Current Developments, February [illegible], 1962
147	An Evaluation of Materials for Rocket-Motor Cases Based on Minimum-Weight Concepts, March 8, 1962
148	The Emittance of Ceramics and Graphites, March 28, 1962
149	Methods of Strengthening the Ultrahigh-Strength Steels, April 2, 19[illegible]
150	Compilation of Tensile Properties of High-Strength Alloys, April [illegible]
151	Compatibility of Propellants 113 and 114B2 with Aerospace Structural Materials, April 27, 1962
152	Electron-Beam Welding of Tungsten, May 21, 1962
153	Brazing and Bonding of Columbium, Molybdenum, Tantalum, Tungsten and Graphite, June 11, 1962
154	The Effects of Decarburization on the Properties of Ultrahigh-Strength Steels, June 18, 1962
155	The Effects of Solutes on the Ductile-to-Brittle Transition in Refractory Metals, June 28, 1962